The Upper-Layer Circulation of the Japan Sea and the Arabian Marginal Seas and Gulfs: Historical Data Analysis

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LONG-TERM GOALS

The circulation of the Japan Sea is characterized by significant temporal and spatial variability due to several factors, including seasonal fluctuations in the warm inflow through Tsushima Strait, branching of the Tsushima Warm Current downstream of the strait, and the formation of mesoscale eddies along these branches. The long-range objective of the Japan Sea study is to understand the dynamical processes that govern this variability. The long-range objective of the Arabian Marginal Seas and Gulfs (AMSG) study is to better understand the relationship between the vigorous atmospheric forcing of the AMSG and the response of the upper ocean in order to be able to better predict the evolution of water properties and upper ocean currents.

OBJECTIVES

Our objectives for the Japan Sea work were to:

1. Describe the synoptic three-dimensional structure of the branching of the Tsushima Warm Current and its seasonal variability.

2. Describe the spatio-temporal modes of variability in dynamic height and determine the primary sources of this variability.

3. Provide a better description of the origin of the Tsushima Warm Current in the East China Sea and seasonal variability in its T-S characteristics.

For the AMSG work, our objectives are:

1. To investigate the seasonal variability in water mass characteristics and distributions in the Arabian Gulf.

2. To describe the structure and seasonal variability of the major fronts and eddies in the upper ocean of the Gulf of Oman and northern Arabian Sea.

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14. ABSTRACT

The circulation of the Japan Sea is characterized by significant temporal and spatial variability due to several factors, including seasonal fluctuations in the warm inflow through Tsushima Strait, branching of the Tsushima Warm Current downstream of the strait, and the formation of mesoscale eddies along these branches. The long-range objective of the Japan Sea study is to understand the dynamical processes that govern this variability. The long-range objective of the Arabian Marginal Seas and Gulfs (AMSG) study is to better understand the relationship between the vigorous atmospheric forcing of the AMSG and the response of the upper ocean in order to be able to better predict the evolution of water properties and upper ocean currents.

15. SUBJECT TERMS

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3. To examine the spatial and temporal characteristics and origin of the large, anticyclonic eddies found regularly in the Gulf of Aden through data analysis and data-model comparison.

APPROACH

We used the very large AXBT data set from NAVOCEANO to investigate a) the structure and distribution of intrathermocline eddies and b) the seasonal variability in the three-dimensional, synoptic temperature structure and circulation in the East China, southern Yellow and southeastern Japan/East Seas in the upper 400 m. Previously, we converted the vast store of XBT data to dynamic height following the methods of Lagerloef [1994] to address Objective 2), but found that the error estimates were not random scatter, as hoped and as was the result in the Gulf of Alaska (where Lagerloef's study was conducted), but biased due to the profound effect salinity has on density structure in the Japan/East Sea. Therefore, we decided to focus more on the unique AXBT data set provided through NAVOCEANO and investigate the synoptic temperature structure and its variability.

We are similarly making use of historical hydrographic and AXBT data from NAVOCEANO to examine the spatial and temporal variability of water properties in the AMSG region. We also plan to collaborate with John Kindle at NRL in the investigation of the Gulf of Aden eddies using the NRL Indian Ocean model that assimilates altimetric data.

WORK COMPLETED

A study of intrathermocline eddies was completed and the results were published in the *Journal of Physical Oceanography* [Gordon, et al. 2002]. A second study of the temperature structure and circulation in the East China Sea, Yellow Sea and Japan/East Sea was completed and a manuscript was submitted for publication in *Deep-Sea Research* in June 2002 [Furey and Bower, 2002, submitted]. This grant has now ended.

For the AMSG project, a study of the hydrographic structure of the Persian/Arabian Gulf and its seasonal variability was completed and a manuscript is in press at the *Journal of Geophysical Research*. Also, an initial study of the velocity structure of Gulf of Aden eddies, and their impact on Red Sea Water spreading, was completed and a manuscript is in press at *Geophysical Research Letters* (funded jointly by ONR and NSF).

RESULTS

The paper on the synoptic temperature structure of the East China, southern Yellow and southeastern Japan/East Seas focuses on four unique AXBT surveys that provide high-resolution coverage of these regions, providing the first synoptic view of quasi-seasonal (September, February, and May) surface to 400-meter temperature structure for this region. Over the entire region, we focus on mixed layer depth dynamics and temperature front structure at the surface, sub-mixed layer (60 meters) (Figure 1), and deep (100 meters) levels. Surface temperature structure is indicative of deeper temperature structure only in winter, when strong monsoonal winds mix the stratified water column often to the bottom (see red dashed line of Figure 1), and spring, before surface heating re-stratifies the water column. The two September surveys illuminate the possible differences in temperature structure. In 1992, the eastern Kuroshio temperature front (Kuroshio Front) is far on-shelf of its usual position between the 200-meter isobath and the mean Kuroshio path [Isobe, 1999a,b], blocking formation of eddies north of Taiwan, and branching into the Tsushima Strait. In 1993, the September Kuroshio Front is found off-shelf of

its winter and spring position, and eddies have formed north of Taiwan, bringing cooler deep Kuroshio water onto the shelf [Tang, et al., 2000]. Despite the 1992 Kuroshio Front anomaly, subsurface temperature fronts through the Tsushima Strait exhibit a seasonal pattern that is consistent with SST fronts [Hickox, et al., 2000], where a front develops southeast of Cheju Island in both summers, and migrates north of Cheju Island in winter and spring. Possible downstream affect of the onshore position of the Kuroshio Front may be the off-shelf direction of the front through the western channel of the Tsushima Strait (Figure1a), whereas in 1993, the September fronts in the eastern and western strait channels followed the Honshu coast once entering the Japan/East Sea (Figure 1d).

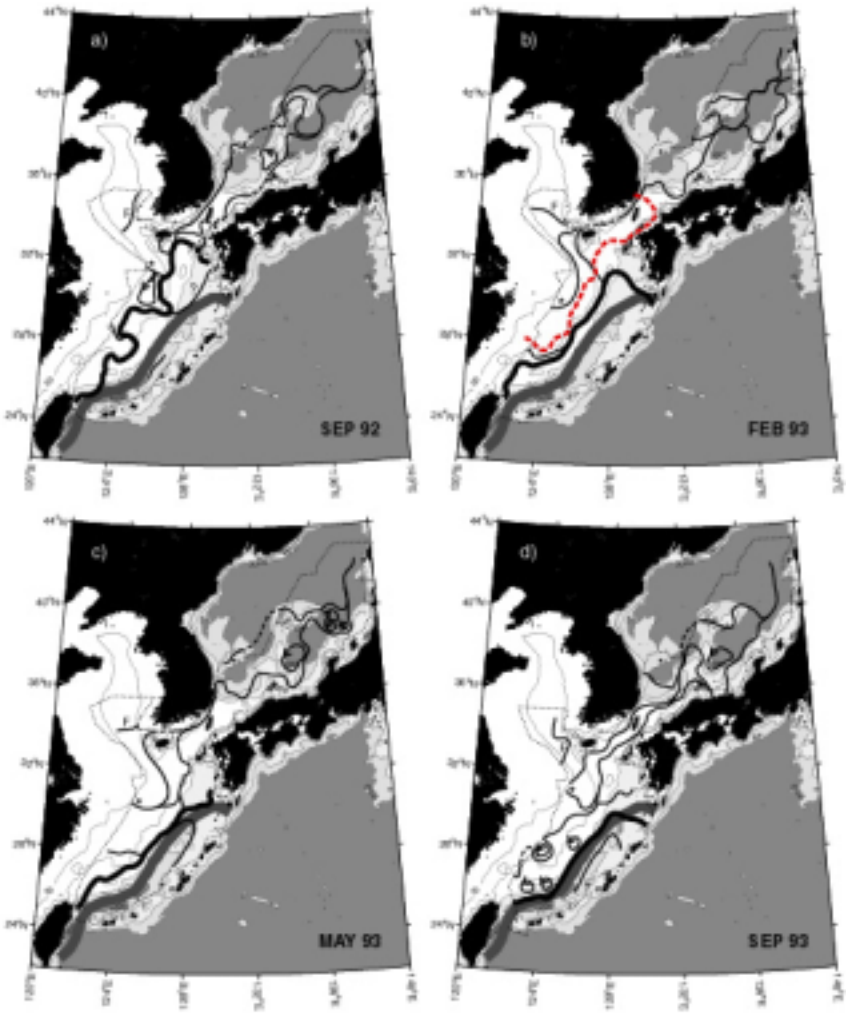

Figure 1. Sixty-meter temperature front structure for a) September 1992, b) February 1993, c) May 1993, and d) September 1993. Fronts have been defined as ~δT>3℃ over 40 km distance (roughly the station spacing). Mean Kuroshio path (taken from Sun and Su, 1994) is shown as a wide gray line. Survey boundaries are drawn as dotted lines. The 100-, 200-, and 1000-meter isobaths are drawn, and bathymetry is shaded every 1000 meters. The red dashed line of b) defines the boundary of the region (to the northeast) where the water column is well-mixed (uniform to within 0.1℃) to the bottom. Heavy black line in ECS is the eastern temperature front of the Kuroshio.

In addition to the regional results, we also focus on inflow and outflow of the Tsushima Strait and, using seven other AXBT surveys that cover the Tsushima Strait outflow region in the JES, we describe branching structure of the Tsushima Warm Current for the years 1992-1995. The East Korean Cold Current can be seen in summer only, reaching back into the western strait as far as the southern end of Tsushima Island. There is evidence of previously undocumented cold water entering the strait from the southwest, appearing to originate from upwelled water near the entrance of the strait. Branching patterns are not seasonally dependant, and fall into three categories: a) one front following the Honshu coast, b) two fronts splitting, one following the Honshu coast, and one following the East Korean Coast (the East Korean Warm Current), and c) similar to b), but with the East Korean Warm Current appearing displaced to the east.

The nature and circulation of water masses in the Persian/Arabian Gulf (the Gulf) was investigated by examination of a historic data base of hydrographic observations. The densest water forms in winter at the northern end of the Gulf rather than along the warmer southern and western coasts. With the exception of small amounts of water directly above the seafloor, most water flowing out of the Gulf mixes across a density front that separates Gulf Deep Water within the Gulf from the Indian Ocean surface water (IOSW). Contrary to previous inferences, the seasonally-variable incursion of IOSW into the Gulf peaks in late spring. This timing may be due to seasonal changes in sea surface slope driven by variations in evaporation rate. In order to explain mooring results published elsewhere that show relatively small seasonal changes in the volume flux through the Strait, we suggest that this flux is driven by the difference between the density of Gulf Deep Water in the interior of the basin and water at comparable depths outside the Gulf. This density difference varies less than 15% during the year. High rates of vertical mixing in the Strait extend about 200 km westward in response to topographic constriction of tidal flows by islands and shoals.

New oceanographic observations in the Gulf of Aden in the northwestern Indian Ocean have revealed large, energetic, deep-reaching mesoscale eddies that fundamentally influence the spreading rates and pathways of intermediate-depth Red Sea Water (RSW). Three eddies were sampled in February 2001, two cyclonic and one anticyclonic, with diameters 150-250km. Both cyclones had surface-intensified velocity structure with maxima ~0.5 m s^{-1}, while the equally-energetic anticyclone appeared to be decoupled from the surface circulation. All three eddies reached nearly to the 1000-2000 m deep sea floor, with speeds as high as 0.2-0.3 m s^{-1} extending through the depth range of RSW. Comparison of salinity and direct velocity measurements indicates that the eddies advect and stir RSW through the Gulf of Aden. Anomalous water properties in the center of the anticyclonic eddy point to a possible formation site in the Somali Current System.

IMPACT/APPLICATIONS

Our results provide a better description of the water properties and seasonal variability in the upper-ocean circulation of the East China and Japan/East Seas, and its causes. The AXBT data sets have been particularly valuable for understanding the synoptic subsurface water mass structure in this region over a very large area, a view usually reserved for remote sensing studies of the surface ocean. Subsurface synoptic temperature structure aids understanding of previous [e.g., Hickox, et al., 2000] and future remote sensing studies. The large-scale synoptic nature of the surveys provides a context and reference point for future work in these regions. The study of Persian Gulf hydrography is the first comprehensive attempt to establish a seasonal climatology for that basin, and the Gulf of Aden eddies paper documents the structure of these large, energetic eddies for the first time.

TRANSITIONS

Knowledge gained in these studies will help oceanographers better understand the processes that determine the circulation in marginal seas and gulfs.

RELATED PROJECTS

The Japan/East Sea project was part of the Departmental Research Initiative in the Japan Sea. Our work will relate particularly to that of Drs. Watts and Wimbush who will be making new observations of the mesoscale variability in the southern Japan Sea, as well as Dr. Arnold Gordon who is investigating intrathermocline eddies in recent hydrographic observations. Our study of Gulf of Aden eddies will help in the evaluation of NRL's Indian Ocean model that assimilates altimetric data, and is tightly related to the NSF-funded Red Sea Outflow Experiment (REDSOX), for which the Pis are A. Bower, D Fratantoni, W. E. Johns and H. Peters.

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